function. Equation (2) holds for direct transitions, i.e., for $\mathbf{k}_e + \mathbf{k}_h \cong 0$, where $\mathbf{k}_e$ and $\mathbf{k}_h$ are the wave vectors of electron and hole, respectively.

The Schrödinger equation is expressed in terms of dimensionless field-independent parameters and transformed with parabolic coordinates $\zeta = |\mathbf{r}| + z$ and $\eta = |\mathbf{r}| - z$, which allow separation into two independent equations. These are numerically integrated considering the correct asymptotic solutions to obtain the eigenvalues E_n and eigenfunctions $\phi_n(\mathbf{r})$. From these, the density-of-states function $\phi^2(\omega)$ is calculated:

$$\phi^2(\omega) = 4\pi^2 a^3 \sum_n |\phi_n(\mathbf{r}=\mathbf{0})|^2 \; \delta[(E_g + E_n - \hbar\omega)/R], \tag{3}$$

with the exciton Rydberg constant R and the exciton Bohr radius a. This finally gives the imaginary part of the dielectric function $\epsilon_2(\omega)$:

$$\epsilon_2(\omega) = \tfrac{4}{3}\epsilon_0\epsilon_r|\mu_{cv}/ea|^2\phi^2(\omega), \tag{4}$$

where μ_{cv} is an interband dipole-matrix element and $\epsilon_0\epsilon_r$ is the static dielectric constant. To include collisional broadening[3,8,24,25] the resulting spectra are convoluted with a Lorentz function with a full width half maximum of 7 meV.

In order to calculate the actual light transmission, we employ a transfer-matrix method[26,27] for the electromagnetic wave equation. This allows to account for inhomogeneous field distributions resulting in different signal contributions from different depths of the active layer. The theoretical DTS for comparison with the experimental results are obtained according to Eq. (1). An inclusion of the light hole contribution[2,8,20] would lead to a superposition of heavy-hole and light-hole oscillations for higher energies. We calculate the spectral deviation to be less than 2 meV and thus neglect this effect in our model.

The dashed lines in Fig. 1 show theoretical calculations of the DTS using the complete theoretical method outlined above. The calculated and experimental spectra agree quantitatively. The temporal evolution of the amplitude as well as the oscillation period is well described. In the following, we discuss a comparison of the experimental results with calculations where nonuniform field distributions and excitonic effects have been neglected. This comparison shows that both effects are essential for a qualitative and quantitative agreement of experiment and theory.

The solution of the Schrödinger equation is given by Airy functions, if the Coulomb interaction between electrons and holes is neglected. Figure 3 shows a comparison of the calculated DTS with and without Coulomb interaction, using the same band gap of E_g=1.428 eV. It is obvious that a quantitative agreement with the experimental data cannot be achieved by a simple Airy-function approach. The omission of the excitonic effects decreases the amplitude at the band edge by more than a factor of 2 and leads to a phase shift of the spectra above the band edge. The spectral position of the extrema as well as the decrease of oscillation amplitude for higher energies are only well reproduced by the full model.

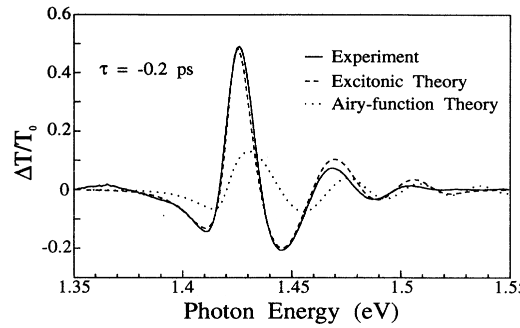

FIG. 3. Experimental and calculated DTS with and without Coulomb interaction.

Figure 4 shows a calculation assuming that the electric fields are homogeneous and switched between 0 and 15 kV/cm. The experimentally observed signal reduction towards higher energies cannot be reproduced, which can be regarded as evidence that a nonuniform field is present in the GaAs layer. An alternative explanation for the damping of the FK oscillations at higher energies would be an energy-dependent damping constant. However, this explanation is immediately ruled out by the very good agreement between experiment and theory for zero time delay, when the field is homogeneous (see Fig. 3).

In conclusion, we have presented experimental and theoretical results for the time-dependent Franz-Keldysh modulation of the optical transmission of a thin GaAs film. The transient electric field has been calculated by a drift-diffusion model and is found to be nonuniform. The optical effect of field modulation is calculated from a Schrödinger equation including the Coulomb interaction potential. Theoretical spectra are calculated by a transfer-matrix method. We find a very good agreement between experiment and theory. To our knowledge, this is the first study which combines both a self-consistent calculation of the drift-diffusion transport and excitonic effects in the optical spectra to understand the time development of an inhomogeneous electric field in a semiconductor structure on a femtosecond time scale, which is of central importance for ultrafast photonic switching.

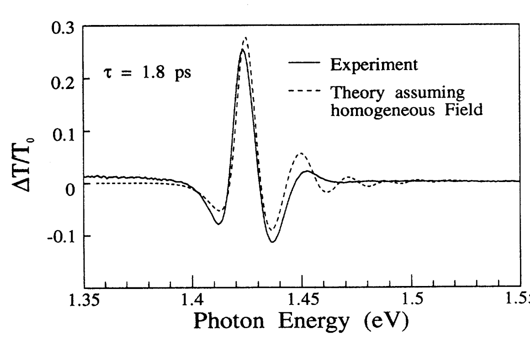

FIG. 4. Experimental DTS at τ=1.8 ps compared with calculation assuming that the field is switched between 0 kV/cm and an average (homogeneous) field of 15 kV/cm.

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